RADIATION DOSES IN INTERPLANETARY FLIGHT

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A gross survey of data on Van Allen belt radiations, galactic cosmic radiation, and solar cosmic radiation, will be presented. On the basis of these data, that still contain uncertainties, upper and lower limits of rad doses which would have been encountered in the past solar cycle under practical amounts of mass shielding are estimated. From the order of magnitude of the physical doses, the following conclusions are tentatively drawn.

The overall ionization dosage produced by the low-level galactic cosmic radiation should not have serious or discernible later effects after expeditions of 1 to 2 years. Mass shielding up to 80 g/cm^2 would not reduce the ionization dosage, but would shield against heavy primaries and heavy ionizing secondaries and would thus reduce the biological dose. The flux of energetic protons in the maximum intensity zone of the inner Van Allen belt is by about 4 orders of magnitude higher, their energy and penetration power, of course, lower. These proton dose rates and also the electron and x-radiation dose rates under some g/cm^2 shielding of low z-number materials will not constitute a radiation hazard for flights straight through the inner belt in 10 minutes and outer belt in 2 hours, times typical for Pioneers III and IV. Staying within the maxima of the belts for a duration of 2 days even inside a shield with a thickness equivalent to 25 cm water would, however, lead to a proton dose of 200 rad, the critical limit for radiation sickness.

Extreme and therefore hazardous solar cosmic ray events, i.e., showers of high-energy protons mainly, of high intensity and a duration of days, occurred with a frequency of 1 to 4 per year during the last highly active solar cycle. For the penetrating, most intense high-energy event of February 23, 1956, the dose within 10 g/cm^2 is estimated to have been below acute limits. In most other cases observed, because of the steep slope of the energy spectra, the dose decreases rapidly with penetration depth. On the surface of the body the dose would, however, be higher and could reach in a lightly shielded space vehicle or for a stay on the moon in a space suit, 1000 rad or more. Without adequate protection such surface doses would even have been surpassed in a planetary expedition over the two years 1959 and 1960, a period in which five extreme events occurred.

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INTRODUCTION

We know at present three kinds of energetic space radiations which may constitute a potential radiation hazard in interplanetary flight. If we set out to an interplanetary space flight from a latitude below 65°, we encounter first the Van Allen belt radiations, i.e., mainly protons and electrons of substantial energy and intensity trapped within doughnut shaped regions symmetrical with the equatorial plane. Near the poles we would encounter normal cosmic or so-called galactic cosmic radiation, i.e., 85 percent protons, 13 percent α particles and 2 percent heavier nuclei stripped of all electrons, of extremely high energy, but of very low intensity. In free space these primaries arrive from all directions of the sky with equal intensity.

During solar active years solar cosmic radiation is encountered in interplanetary space. This radiation is identified during the international geophysical year as transient energetic particle showers, mainly protons associated with flares on the sun. Flares are intense chromospheric light flashes in the ultraviolet and visible part of the spectrum accompanying violent plasma eruptions on the sun's surface. In some cases the particle streams encountering the earth have an intensity that is 4 to 5 orders of magnitude higher than that of galactic cosmic radiation and have a duration of the maximum phase in the order of 1 day. Low intensities are still observed 10 days after the flare. In the following discussion, doses that would have been received in space vehicles of different wall thicknesses by these three kinds of radiation during the most solar active years of the last cycle are estimated on the basis of spectral data available until 1962.

VAN ALLEN BELT RADIATIONS

Figure 1 represents a schematic survey of fluxes and energies of particles within the Van Allen belts taking into account the more detailed measurements obtained with Explorer XII, Fall 1961 (see refs. 1 to 5) before the changes induced with the nuclear high-altitude test Starfish in July 1962. The flux contours of electrons are given on the left side, those of protons on the right.

Fig 1

The most important belt radiation from the viewpoint of implications to space flight are the high-energy protons from 30 to 700 Mev energy which are mainly encountered in the inner belt with maximum intensity of 20×10^4 to 40×10^4 protons/cm^2-sec in an altitude of about 3000 km.

Fig 2

Based on Freden White's spectrum, the following doses in the belt center as functions of shielding are obtained (see fig. 2*):

For	2 g/cm^2	outer shield	24 rad/hour
	25 g/cm^2	outer shield	6 rad/hour

*The figure is based on $N = 20{,}000\ p/cm^2\text{-sec}$, $E > 40$ Mev in the center of the belt.

if we assume 40,000 protons/cm^2-sec $E > 40$ Mev as the upper flux limit in the center of the belt. These are upper limits of dose rates since self-shielding of the human body is neglected and the spectra fall off steeper on other locations of the belt.

The low-energy protons $E > 5$ Mev contribute only to doses on the surface of the vehicle since their range is below 0.05 cm in water or 0.06 g/cm^2 in material of larger atomic number. The low-energy electrons $E > 10$ kev to 1.6 Mev have fluxes in the order of 10^8 to 10^9 electrons/cm^2-sec and vary in intensity with time less than the high-energy electrons having energies above 1.6 Mev. The latter are extremely variable in intensity during magnetic disturbances, having low fluxes in the order of 10^5 to 10^3/cm^2-sec only. The natural electrons appear not to be very important from the viewpoint of radiation doses inside a vehicle with a few g/cm^2 wall thickness. The x-radiation dose rate amounts to substantially less than 2 rem/hr (2 rad/hr behind 30 mil steel, based on conservative upper limits of spectral fluxes, see ref. 6).

After the nuclear high-altitude test on July 9, 1962, high-energy fission electrons were observed especially within the inner shells of the radiation belts and in lower altitudes. Their maximum intensity is measured to be 2×10^9/cm^2-sec $E > 40$ Mev. They exhibit especially in the high-energy range $E > 2$ Mev markedly higher intensities than the natural belt electrons. The dosage received during passage and return through the maximum intensity zones would nevertheless be substantially below the emergency dose of 25 rem in a space vehicle with some g/cm^2 aluminum or steel walls. According to Van Allen, these electron intensities decay faster than those calculated theoretically from Coulomb scattering. The radiation should therefore return to normal after a few years if no further high-altitude nuclear tests are carried out. A more detailed discussion is deferred until more data on life times of the artificial electrons are available.

In summary, it may be said that the belt radiations do not constitute an acute danger if the belts are passed in about 2 hours, a time which is characteristic for Pioneers III, IV, and V, or escape missions. If we stay in the center of the inner belt for 2 days, however, even with 25 g/cm^2 shielding, the proton dose would be >200 rad. This value is on the critical limit for acute radiation sickness.

GALACTIC COSMIC RAYS

With respect to Galactic Cosmic rays from the viewpoint of implications to space flight, the most important fact is that their flux is low, namely 2.5 particles/cm^2-sec during solar activity years - about 10,000 times lower than the flux within the inner Van Allen belt or during extreme flare proton events; consequently, the overall ionization rate per gram or per cm^3, that is, the physical dose rate is also low. By carefully taking into account the high specific ionization of heavier primaries and their higher RBE* a biological dose rate of 0.45 rem/week (ref. 7) is calculated in free space, secondaries which originate in the spaceship and in the human body itself being neglected.

*Relative Biological Effectiveness, see reference 9.

During solar minimum years the dose rate would be higher by about a factor of 2. This is, of course, many orders of magnitude more than the radiation dose which man receives on sea level under 1000 g/cm^2 atmosphere and under protection of the magnetic field of the earth. However, this dose rate does not surpass substantially the maximum permissible dose rate which is stated for atomic workers according to the recommendations of the International Commission for Radiation Protection (ICRP), i.e., 0.1 rem/week when continuously received over 50 years of professional duty. Shielding against the overall ionization produced by galactic cosmic rays appears impractical for the present generation of space vehicles since up to 80 g/cm^2 wall thickness increases the ionization dose at least during solar activity years when low-energy primaries are diminished. The biological effectiveness or biological dose would, of course, be lower with heavy shielding than without, since the flux of the more heavily ionizing primaries and secondaries is reduced.

Special attention on the part of scientists and biologist is directed to one component of galactic cosmic rays, the heavy primaries. The heavy ionized end of such a heavy primary track (see fig. 3) is by orders of magnitude longer and the ionization is spread over a 10 to 20 fold higher cross section than that of an α particle track (length $\approx 30\ \mu$ cross section $\approx 0.5\ \mu$).

Figure 3

The effect of heavy primary hits on sensitive organs such as the receptor cells of the eye which the body cannot replace is expected to be more important than would be anticipated from their small contribution to the total ionization. The number of hits per cm^3 and per day is, however, very low as seen in figure 4 which shows the number of hits as function of altitude extrapolated by Yagoda (ref. 8) from balloon measurements.

Fig 4

Shielding against this radiation would be an easier task. A residual air layer of 36 g/cm^2 (75,000-ft altitude) would reduce the number of hits by a factor 40 during solar minimum years and by a factor of 6 during activity years.

SOLAR COSMIC RAY DOSES

To estimate flare proton doses in interplanetary excursions on the basis of events of the last solar cycle, one has to go more into detail since the data are in some extreme cases more uncertain. In a planetary excursion which may take years, multiple events in short succession have a high probability. Such series might constitute in intense cases an acute exposure hazard; furthermore, the total dose over a highly solar active period of corresponding duration should be estimated as correct as possible. For these reasons a reevaluation is presented of the May 10 and July 14 and 16, 1959, events which were overestimated on the basis of earlier data and extrapolations. The mentioned July events together with the July 10 event occurred within 1 week. The July series appears to have been the most abundant in terms of particles/cm^2 of the last solar cycle.

To calculate the doses accumulated during the events of July 14 and 16, counter and ionization chamber measurements during balloon ascents are used as basic data. These ascents and flights were carried out by Winckler and co-workers (ref. 10) in Minneapolis and Kinsey Anderson in Resolute Bay (ref. 11), the latter directly on the magnetic North pole (see fig. 5, lower part).

Fig 5

The used spectra are measured on July 15 during balloon ascent in Minnesota about 30 hours after the flare of July 14 and for the third event +14 and +29 hours after the flare on the 16th, in Minnesota and Resolute Bay, respectively (see fig. 6(a)).

The particle intensity below 85 Mev cannot be measured in balloon ascents since particles up to this energy cannot penetrate the residual atmosphere of 7 g/cm^2. These low-energy parts of the spectra are extrapolated according to an exponential rigidity law (see Winckler and Webber ref. 12). In detailed evaluations of balloon data for about 50 ascents, Webber and Freier found that in most cases the integral intensity in a wide energy range is proportional to e^{-p/p_o} rather than to powers of the energy - the rigidity p_o determines the slope of the rigidity spectrum in a logarithmic plot. The energy spectra in a log log plot therefore bend over or flatten toward lower energies earlier and in a higher degree in most cases than was assumed in former extrapolations. A bendover of the energy spectra was also emphasized by D. Bailey (ref. 13) on the basis of ionospheric observations and measurements. The analysis of solar particle data of Fichtel, Guss, Ogilvie (ref. 14) is in general agreement with these lower fluxes except for some events, where the riometer and scintillation counter measurements yield fluxes higher by a factor of 2 to 4 in the energy range 20 to 40 Mev. Also the question of the particle fluxes at very low energies $E < 5$ Mev or the question of the surface doses behind very low shielding or no shielding seems not very clear at present.

From the spectra the dose rate as a function of shielding for that particular instant is calculated at which the spectrum is measured. By multiplication with the time for which the different spectra are valid, the dose as function of shielding is obtained. To obtain rough lower limits of doses in the above cases the +30 hours spectrum on July 15 (July 14 flare) is considered as constant in shape and intensity back to the time of the riometer decrease, i.e., for about 24 hours. For the third event (July 16 flare) the +14 hour spectrum is considered valid for 8 hours and the +29 hours spectrum for 16 hours. The riometer curves (see fig. 5, upper part, taken from Reid and Leinbach ref. 15) in northern latitudes suggest a flux by a factor 1.7 higher, part of the time in the July 14 event, and a flux by a factor 3.5 or 2, respectively, higher at +14 and +29 hours after the July 16 event. As upper limit for the July 14 doses, the above values are therefore multiplied by the factor 1.5. In the July 16 event, also the balloon instruments in Resolute Bay went off scale during the maximum phase and the radiation was apparently omnidirectional from early beginning; therefore a factor of 2 to obtain rough upper limits appears to be justified (see table I).

For the May 10, 1959, intense and extended low-energy event, the spectrum $E > 100$ Mev measured 32 hours after the flare during balloon ascent and flight in Minnesota (refs. 16 and 17) is extrapolated to lower energies corresponding to an exponential rigidity law according to Webber. The four times higher flux values $E > 100$ Mev $N(>100 \text{ Mev}) = 180$ pr/cm^2-sec ster or the four times higher spectrum given in reference 16, on which earlier estimates are based, are apparently not valid for extended duration and are therefore here abandoned. As a duration of the former spectrum, 36 hours is assumed according to the envelope of the riometer curves in high latitudes. (See ref. 15.) The obtained doses are considered as rough estimates; the calculation of upper and lower limits is deferred until more data are available. In figures 6(a), 6(b), and 7, and in table I, further spectra and doses for the February 23, 1956 and the November 12, 1960 events are indicated which are discussed with references and basic data in reference 9, in which dose calculations are outlined in detail.

The result of this reevaluation of doses can be summarized in the following way: The intense low-energy events of May and July 1959, do not constitute a separate group which surpasses with its low-energy fluxes or doses at low shielding the November 12, 1960 event, as concluded in earlier extrapolations. The extreme medium- and low-energy events of the last solar cycle yield doses, which lie in the broad strip with steep slope in figure 7, having about as upper limit the doses of the November 12, 1960 event.

From the steep decrease of most spectra for energies >80-100 Mev and, consequently, the steep fall off of doses with shielding thickness, and their absolute values, one can conclude that the main problem will probably be surface doses at low-shielding thicknesses and that the doses fall off very fast in men's bodies itself. The high-energy event of February 1956, is, of course, more penetrating; its time integrated fluxes and doses in the depth, however, apparently did not surpass the limits for acute radiation sickness.

The doses given in figure 7 are upper and lower limits of rad as measured in a small ionization chamber in the center of spherical shields of different thicknesses (abscissa), self-shielding of man's body inside the shield being neglected. If the shield consists of water, the g/cm^2 on the abscissa give the thicknesses of the shields in cm. For more realistic appraisal of the surface and depth dose within the human body, it has to be taken into account that organs in the depth of the body receive doses which are obtained from figure 7 by adding to the outer shield thickness the average thickness of the surrounding tissue (10 to 15 g/cm^2). Also the doses on the body surface are substantially lower than those read from figure 7 in which only the outer shield is taken into account, because the surface is protected from one side or from a considerable large solid angle through the body itself. A fair approximation of doses received on organs on the surface (skin, eyes, and gonads) is obtained by dividing the above reading by the factor 2; thus, the radiation from one side or from a solid angle 2π is neglected.

Table I

Table I summarizes the flare doses received in a period of $1\frac{1}{2}$ years of high solar activity from May 1959 to November 1960; only major events are listed. Besides the upper and lower limit of doses for each outer shield thickness, in the third column the approximate surface dose is given by multiplying the average by 1/2. The doses range from about 6000 rad on the surface of the body, inside a very low shielding as in a spacesuit of 0.5 g/cm^2 water equivalent, to 30 to 40 rad in the center of the body behind 0.5 to 6 g/cm^2 outer shield.

TOTAL DOSES IN INTERPLANETARY FLIGHTS DURING SOLAR HIGHLY ACTIVE YEARS

As an example for doses which might be accumulated during interplanetary flights of extended duration in highly solar active years, the total dose, that is, the dose produced by solar cosmic rays by galactic cosmic rays and by belt radiation, the latter at fast passage of the belts, for the one and one-half year period of May 1959 to November 1960 are summarized in table II. It might be mentioned that the solar radiation should increase in intensity at flights toward the sun and decrease at distances greater than that of the earth. The gradients are not known until now. The given dose values are therefore rough estimates only, which are surpassed if the spacecraft stays nearer to the sun for extended periods.

In the last line of table II the total dose is given in rem; for solar and belt protons a relative biological effectiveness (RBE) equal to 1.5 is assumed and heavier components and secondaries are neglected.

The doses in the depth of the body are between 80 and 160 rem. These doses do not appear to be alarming and would not lead to disabling symptons because they are distributed over $1\frac{1}{2}$ years. The maximum permissible dose for atomic workers is ≈270 rem during 50 years of professional life. Half of it would then have been experienced by the astronauts in $1\frac{1}{2}$ years. The surface or skin doses are higher and depend strongly on outer shielding. 350 rem for 6 g/cm^2 outer shield is, of course, still below the erythema dose for skin; it is, however, already damaging for eyes and gonads. An acute dose of 400 rem on gonads would lead to 4 years sterility. Distributed over $1\frac{1}{2}$ years such effects would be gradually lower but still not harmless. The eyes are not supposed to receive more than 100 rem at one time and 270 rem distributed over the whole life if cataracts are to be avoided. The above numbers suggest therefore additional protection for eyes and gonads if only 6 g/cm^2 shield can be provided.

At 1 g/cm^2 outer shield, the surface dose of ≈4000 rem appears also too high for the skin. Doses of this order, applied to the skin of the whole body in a period short in comparison to a lifetime, are observed to produce tumors of all pathological anatomical known types on animals. The tumor frequency increases up to 100 percent at 4000 rad-one-time exposure. Again we have to consider that this dose of 4000 rem is distributed over $1\frac{1}{2}$ years; nevertheless, possible erythema would occur and might interfere with full performance of the crew and the chances of serious late effects like cancer on the skin would become high.

Summarizing one might say: If weight limitations allow no higher general wall thickness than a few g/cm^2, a shelter compartment or body protection with wall thicknesses in the order of more than 10 g/cm^2 for times of solar events appear advisable. 25 g/cm^2 for such periods and possibly for the sleeping quarters would substantially reduce the effects of heavy primaries and secondaries. In general men operate in space, also with relative heavy shielding, in a radiation environment which produces an exposure surpassing by a factor of 5 to 10 the maximum continuous dose rate for radiation workers, when received over a lifetime of 50 years. If an extended stay in lightly shielded compartments of the vehicle during intense solar events is necessary, precautions should be taken to protect sensitive organs on the surface of the body and also the skin itself. Thus the radiation problem in interplanetary flight, presuming fast passage of the belts and sufficient distance from the sun, seems less serious in terms of weight as anticipated earlier if high tolerance doses are accepted and if no events occur in the next solar cycles that surpass substantially with respect to size, i.e., time-integrated fluxes, those events which were observed near the earth in the last cycle.

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Figure 1.- Energetic particle fluxes in the Van Allen belt (as of fall 1961), schematic survey.

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Figure 2.- Dose rates in center of spherical shields neglecting self-shielding of the body. (See: Schaefer, Hermann J.: Tissue Depth Doses in the High Intensity Proton Radiation Field of the Inner Van Allen Belt. Rep. No. 16, U.S. Naval School of Aviation Medicine (Pensacola, Fla.), Nov. 10, 1959. Keller, J. W.: A Study of Shielding Requirements for Manned Space Missions. FZK-124 (Contract No. NASw-50), Convair, Oct. 10, 1960. Allen, R. I., Dessler, A. J., Perkins, J. F., and Price, H. C.: Shielding Problems in Manned Space Vehicles. NR-104 (Contract No. DA-01-009-506-ORD-832), Lockheed Nuclear Products (Marietta, Ga.), July 1960.) The rem dose rates are calculated by J. W. Keller assuming for protons and neutrons of $E > 40$ Mev RBE = 1 and of $E < 40$ Mev RBE = 2. The long-dashed line indicates the contribution of neutrons.

(a) Ionization peak and thin-down part of a heavy nucleus track of $Z \approx 50$ (tin) recorded at 105,000 feet and 55° N latitude with emulsion chamber method, by Herman Yagoda, Laboratory of Physical Biology, National Institutes of Health.

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(b) Microphotograph of two sections of a heavy nucleus track $Z = 20$, and a Thorium alpha track (E. P. Ney and Ph. Freier, University of Minnesota). Left, heavy nucleus of 4,000 million ev energy; center, heavy nucleus at 400 million ev energy; right, thorium alpha track; total vertical length of the visual field, 58 micra.

Figure 3.- Heavy primary tracks in nuclear emulsions.

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Figure 4.- Variation of thin-down intensities with altitude for seasons of maximum and minimum sunspot activity. (Taken from ref. 8, H. Yagoda.)

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Figure 5.- Balloon measurements (see Winckler, J. R., et al., ref. 10 and Anderson, K. A., et al., ref. 11) and riometer records (see Reid, G. C., and Leinbach, H., ref. 15) during the July 10th, 14th, and 16th solar events.

(a) July 16, May 10, 1959 and Feb. 23, 1956 spectra.

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(b) Nov. 12, 1960, May 10, 1959 and Feb. 23, 1956 spectra.

Figure 6.- Integral energy spectra of solar cosmic rays, inner belt protons, and galactic primary protons. (References and basic data see in the text and ref. 9.)

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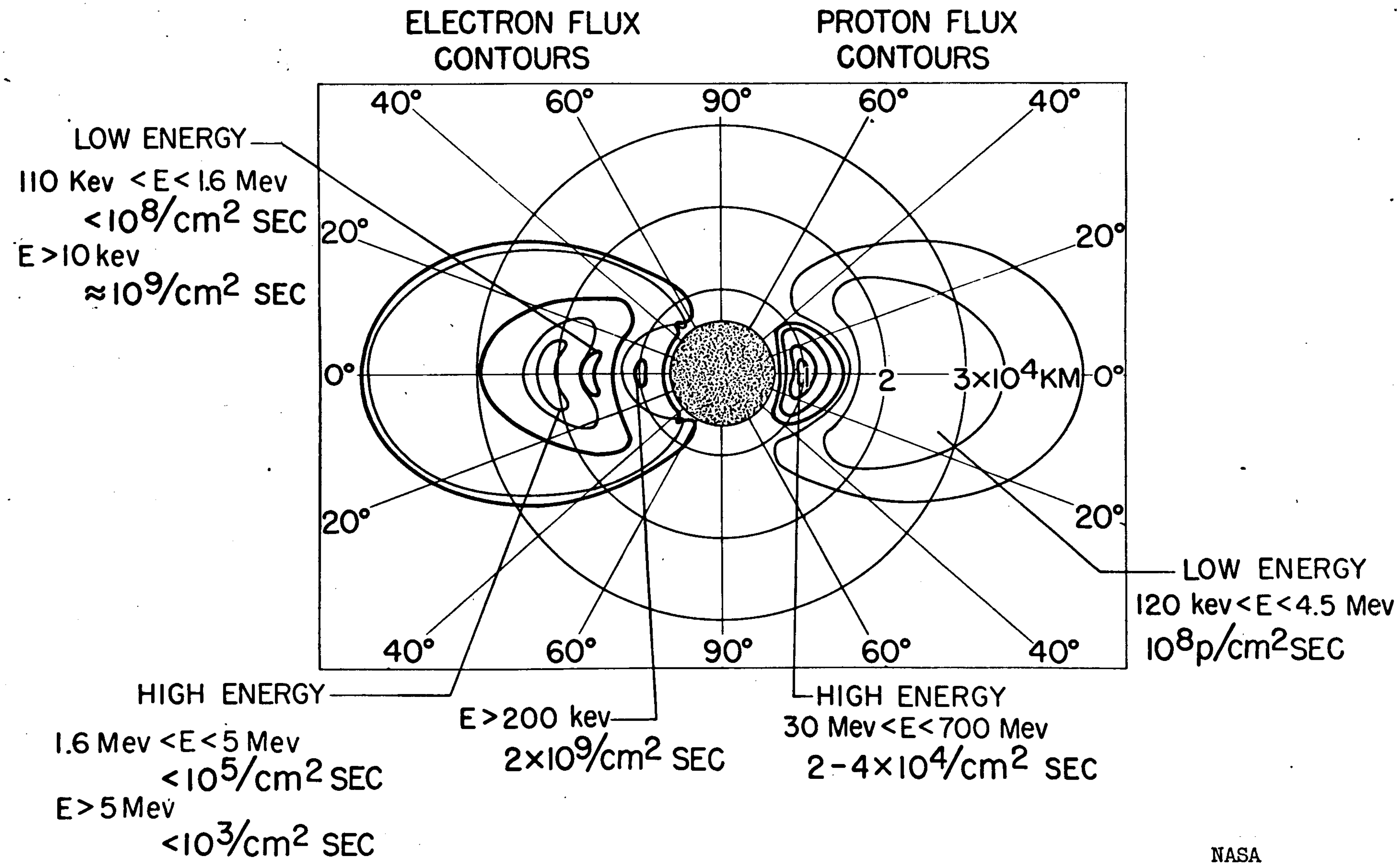
Figure 7.- Flare proton doses in the center of spherical shields neglecting self-shielding, calculated on the basis of the spectra figure 6 and time variations given in the text and in reference 9.

Table I.- Flare Doses May 1959 - November 1960 (neglecting self-shielding).

Table II.- Total Doses in Period May 1959 - November 1960.



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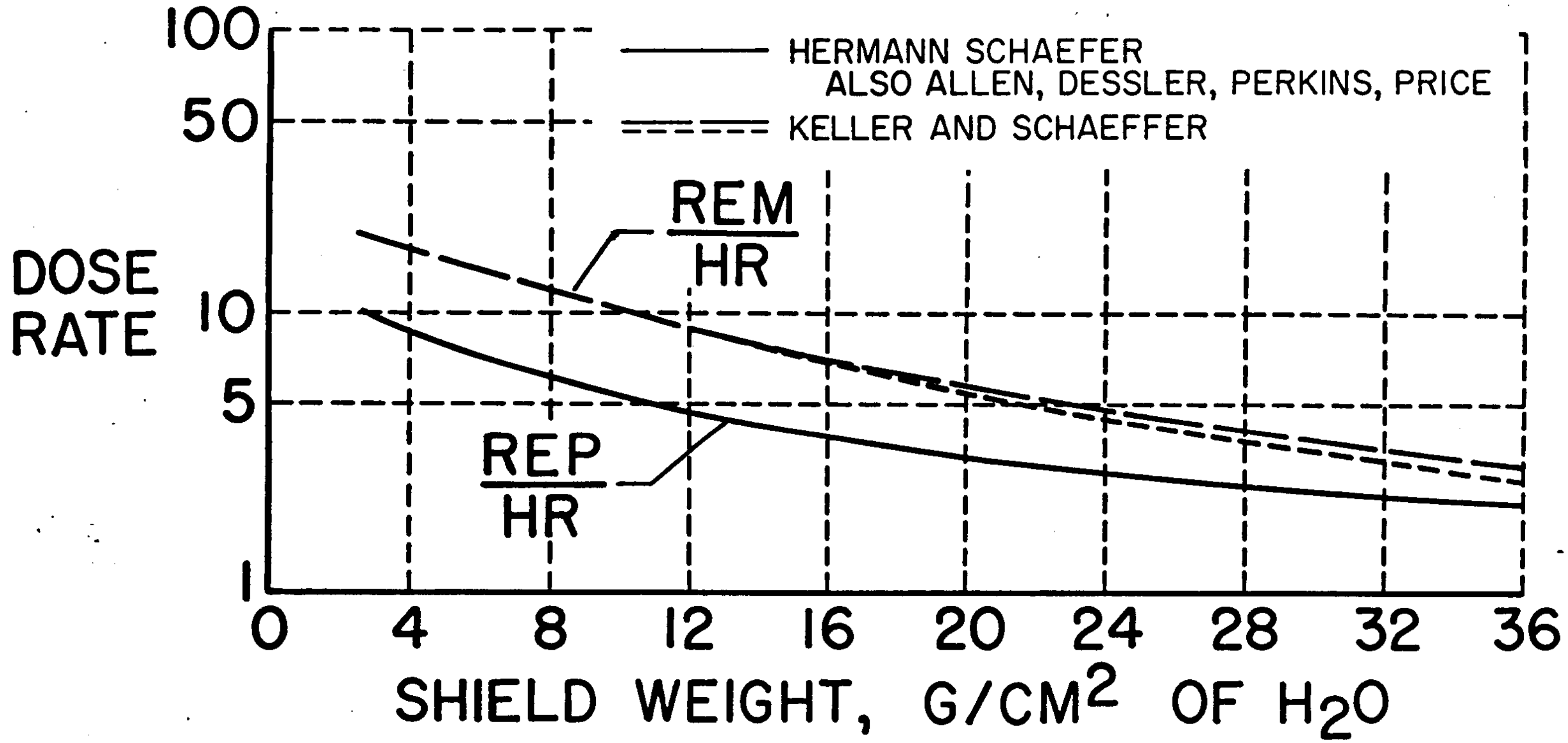

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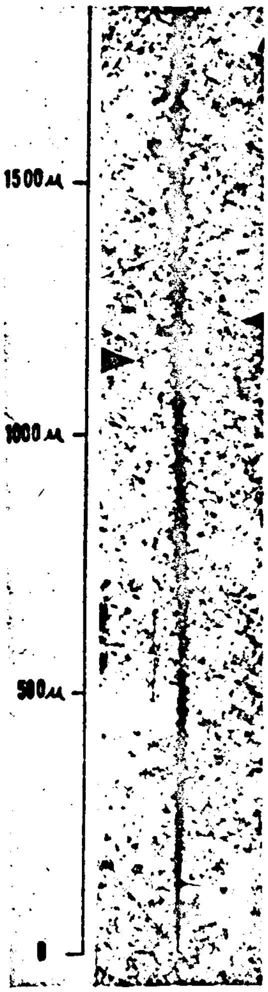

(a) Ionization peak and thin-down part of a heavy nucleus track of $Z \approx 50$ (tin) recorded at 105,000 feet and 55° N latitude with emulsion chamber method, by Herman Yagoda, Laboratory of Physical Biology, National Institutes of Health.

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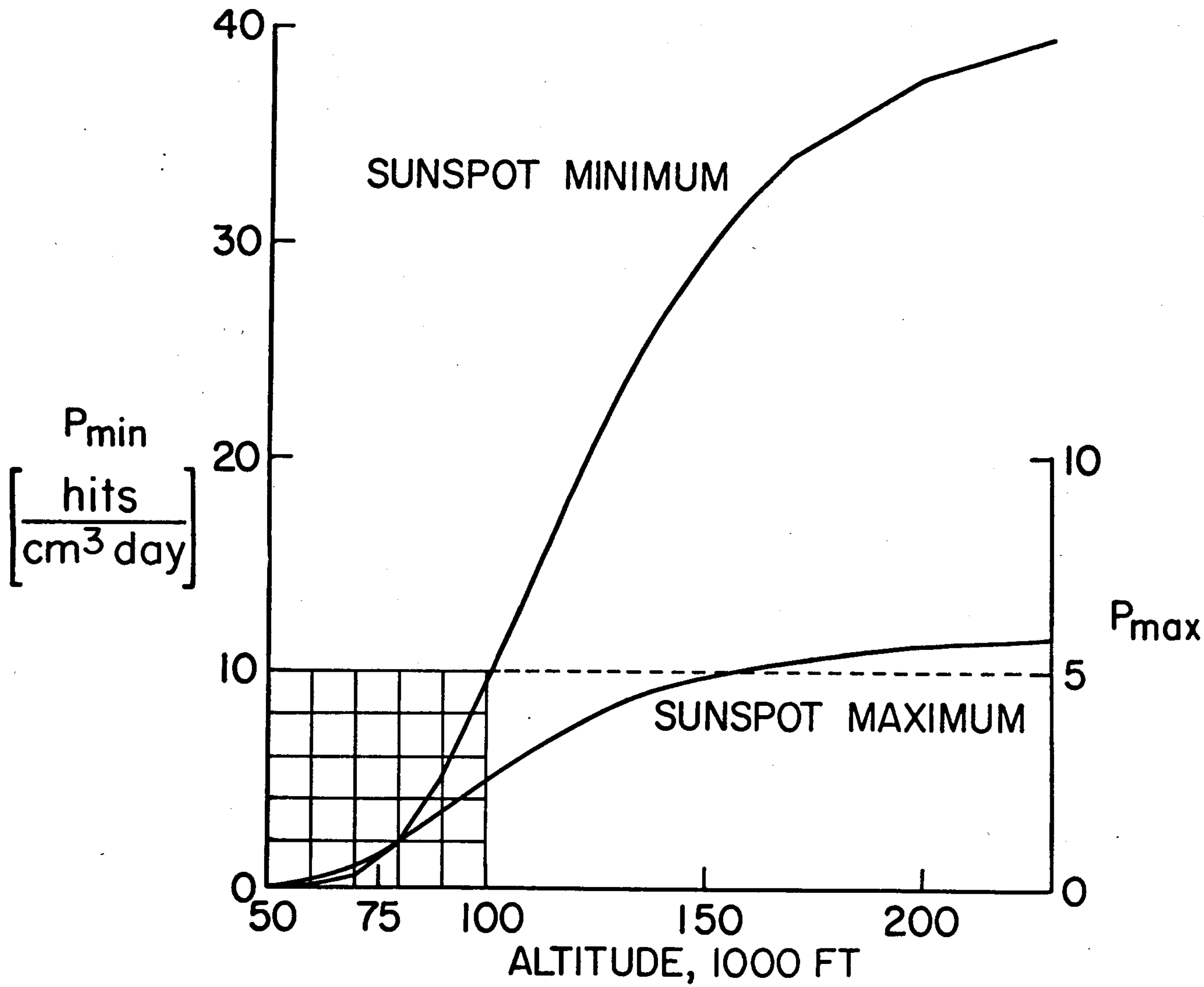

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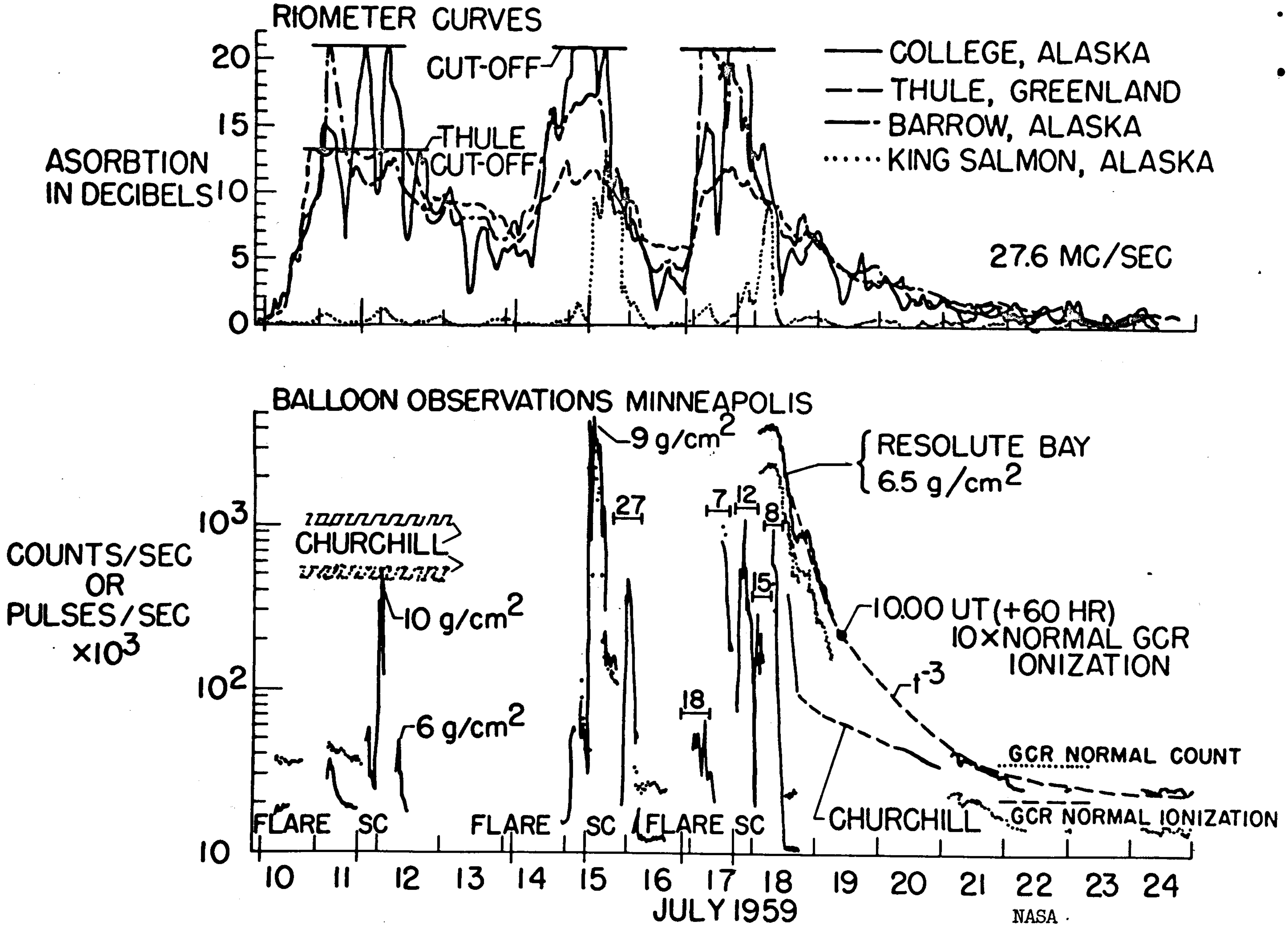

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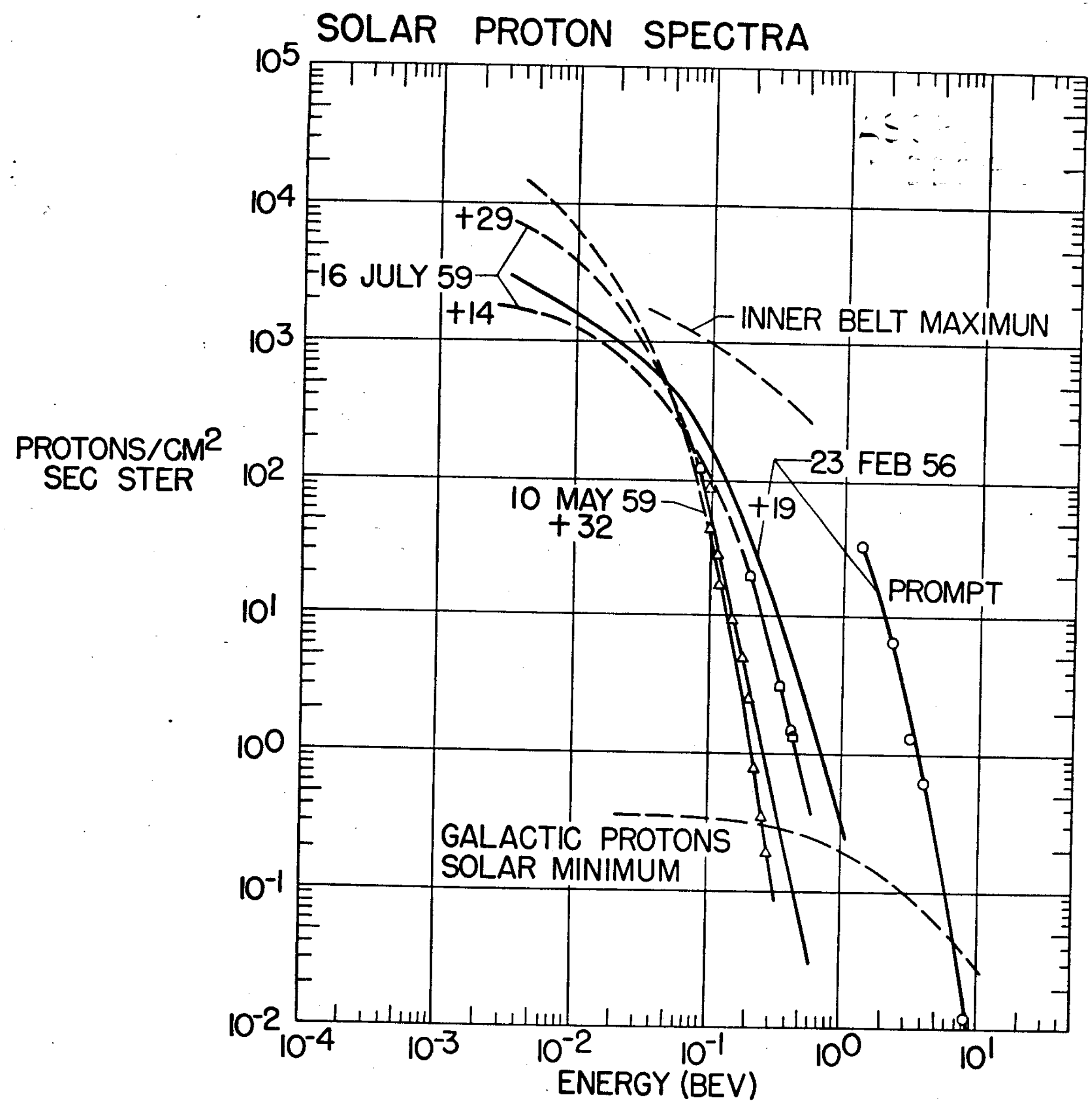

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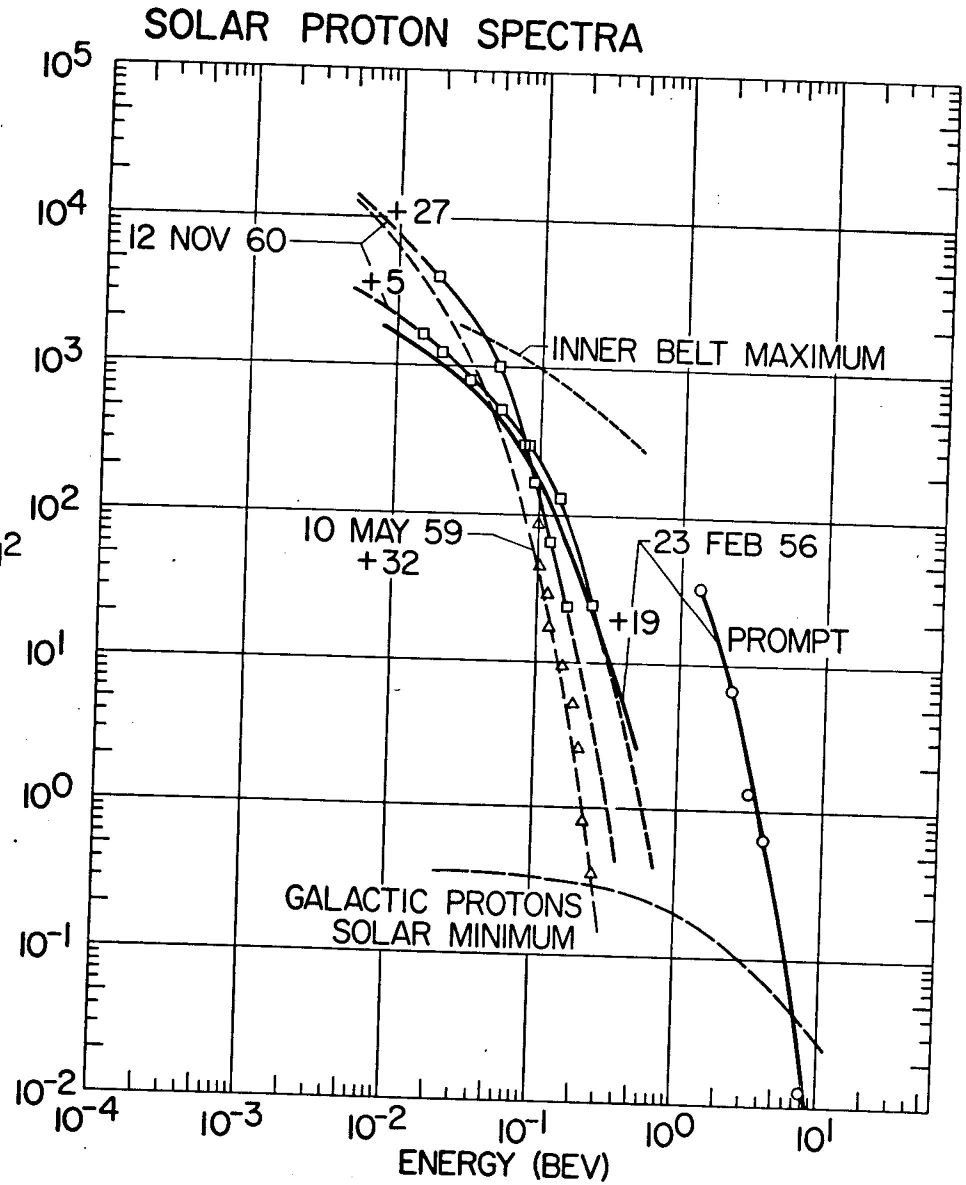
(a) July 16, May 10, 1959 and Feb. 23, 1956 spectra.



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(b) Nov. 12, 1960, May 10, 1959 and Feb. 23, 1956 spectra.

Figure 6.- Integral energy spectra of solar cosmic rays, inner belt protons, and galactic primary protons.

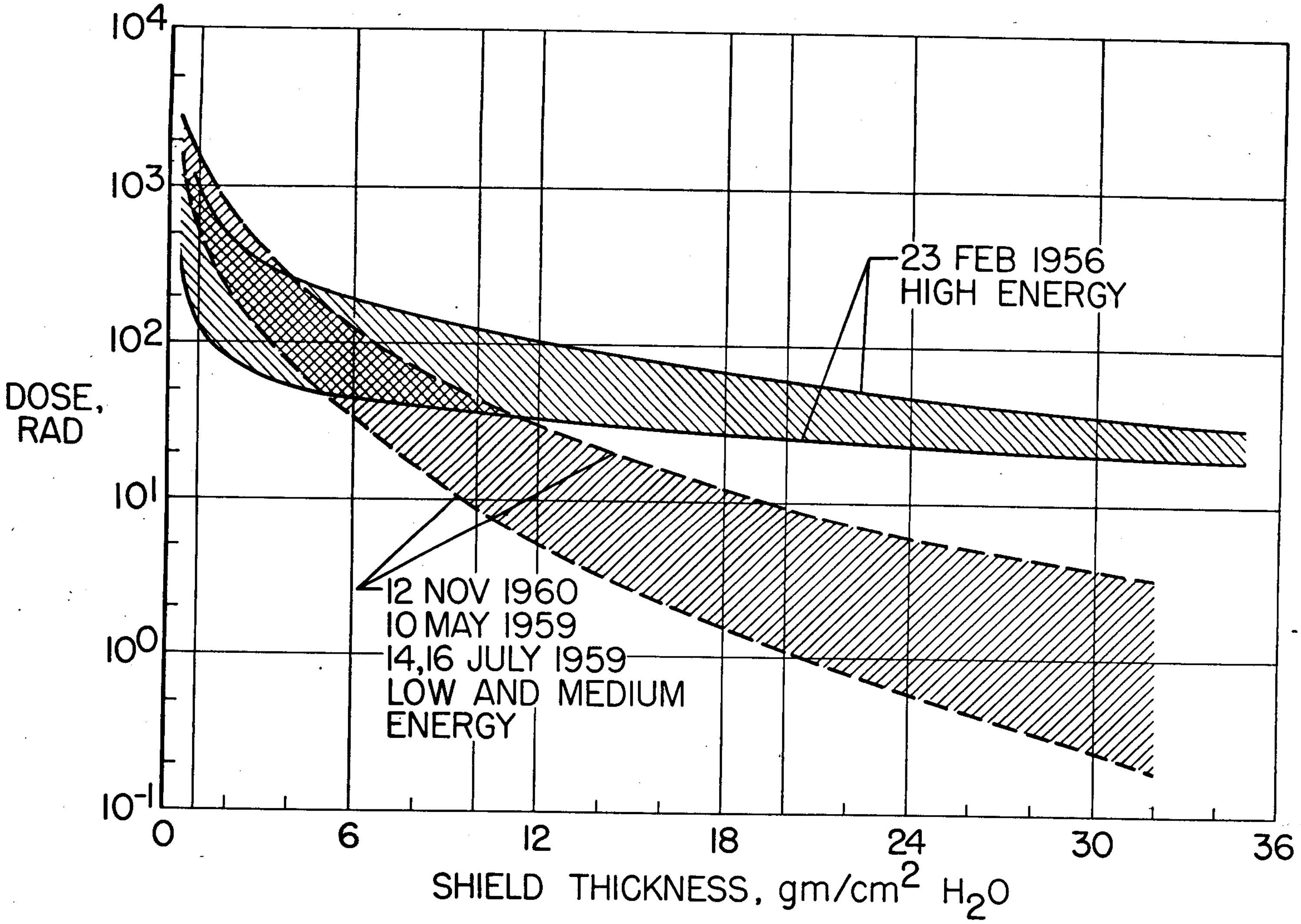

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Figure 7.- Flare proton doses in the center of spherical shields neglecting self-shielding, calculated on the basis of the spectra figure 6 and time variations given in the text and in reference 9.

(NEGLECTING SELF-SHIELDING)

TABLE I

OUTER SHIELD	0.5 g/cm^2			1 g/cm^2			2 g/cm^2			6 g/cm^2			20 g/cm^2	
DOSE, LIMITS	RAD UPPER	RAD LOWER	1/2	RAD UPPER	RAD LOWER	1/2	RAD UPPER	RAD LOWER	1/2	RAD UPPER	RAD LOWER	1/2	RAD UPPER	RAD LOWER
EVENTS:														
MAY 10, 59	≈ 3,700		≈ 1,850	≈ 1,100		≈ 550	≈ 360		≈ 180	≈ 38		≈ 19	≈ 1.1	
JULY 10, 59	≈ 1,000		≈ 500	≈ 450		≈ 225	≈ 240		≈ 120	≈ 47		≈ 23	≈ 3.8	
JULY 14, 59	2,400	1,600	1,000	1,020	780	450	458	305	190	105	70	44	8.7	5.8
JULY 16, 59	2,600	1,300	975	1,000	500	375	400	200	105	76	38	29	5.5	2.7
Σ JULY			≈ 2,475			≈ 1,050			≈ 460			≈ 96		
NOV. 12, 60	≈ 2,700		≈ 1,350	≈ 1,500		≈ 750	≈ 680		≈ 340	≈ 115		≈ 58	≈ 10.5	
NOV. 15, 60	≈ 1,300		≈ 650	≈ 750		≈ 375	≈ 300		≈ 150	≈ 57		≈ 29	≈ 5	
Σ DOSES	13,700	11,600	≈ 6,325	5,820	5,080	≈ 2,725	2,438	2,085	≈ 1,130	438	365	≈ 202	34.6	28.9

Table I.- Flare Doses May 1959 - November 1960 (neglecting self-shielding).

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RADIATION	OUTER SHIELD	BODY DOSE SURFACE	BODY DOSE DEPTH 20 g/cm^2	
SOLAR PROTONS	1 g/cm^2	2725 RAD	30-80 RAD	RBE 1.5
MAY 59 - NOV. 60	6 g/cm^2	202 RAD		
BELTS: p = 24 RAD/HR	2 × 10 MIN	8 RAD	2 RAD	
e^- : 1 REM/HR	2 × 2 HRS	4 REM	2 REM	
GALACTIC C.R. 0.5 REM/WEEK	75 × 0.5 $\frac{REM}{WEEK}$	38 REM	38 REM	
TOTAL	1 g/cm^2	4150 REM	86-160 REM	
	6 g/cm^2	350 REM		

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Table II.- Total Doses in Period May 1959 - November 1960.